New QCD measurements with charm, beauty, and weak bosons at D0

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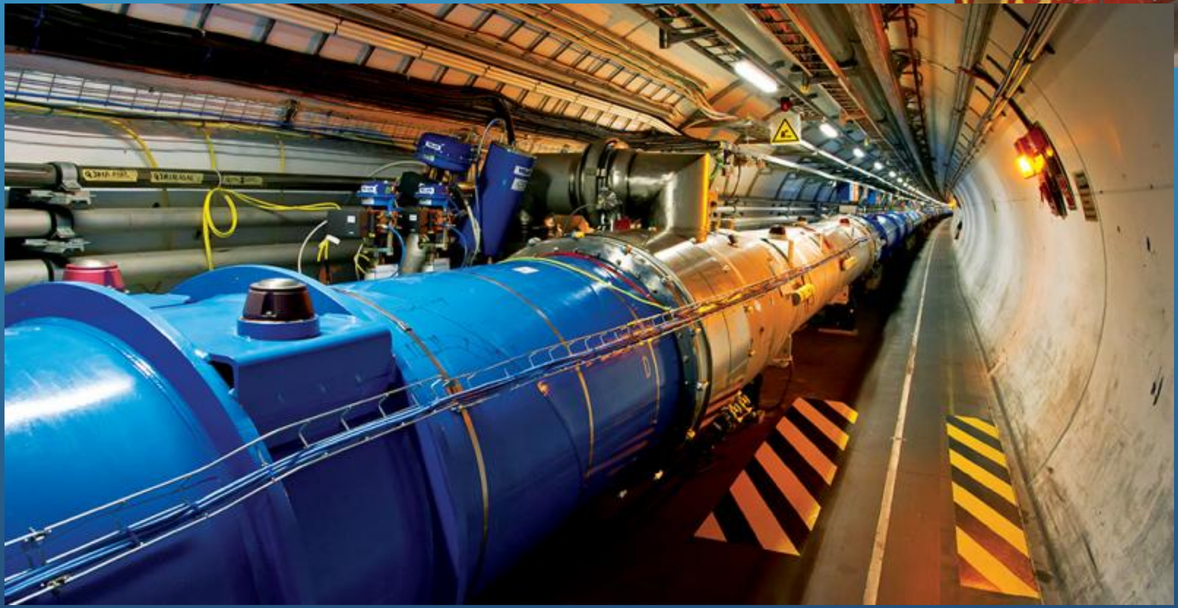
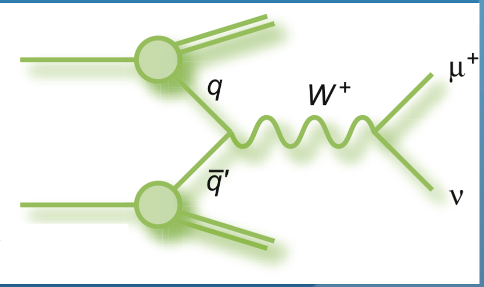
Outline

- Introduction: weak bosons, charm, and strangeness
- W+c, W+b differential cross section measurements
  - W+heavy flavor (HF) processes
  - Previous experimental results
  - Object identification at D0 for V+HF processes
  - Analysis methods
  - Results
- First Z+2b/Z+2j cross section measurement
  - Z+HF process
  - Previous experimental results
  - Analysis
  - Discussion

Weak boson production

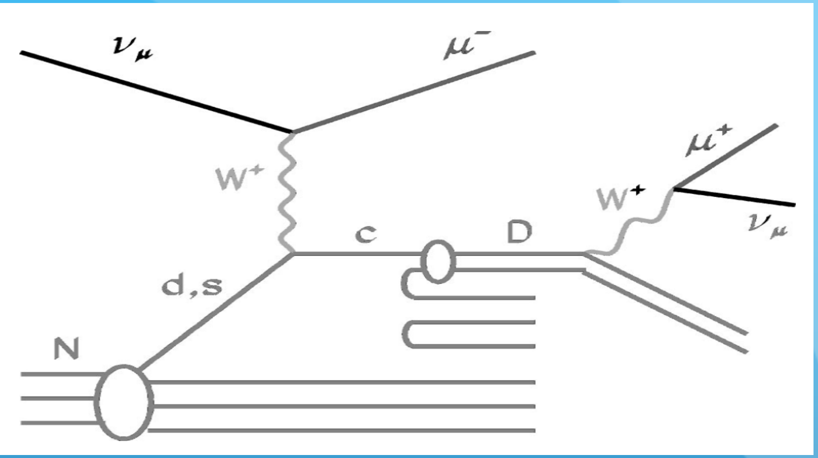
- Produce weak bosons on shell
- Particle accelerators
- Hadron colliders



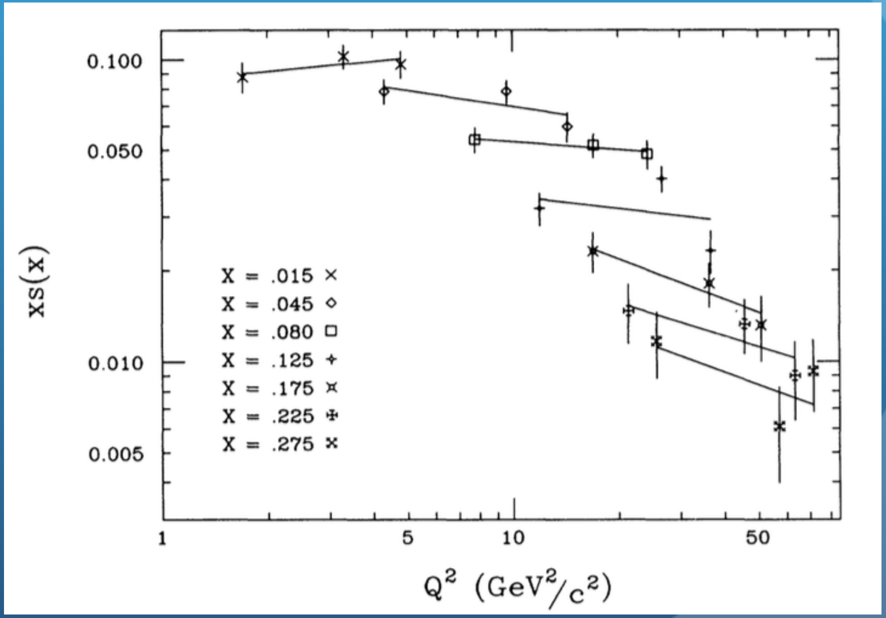


Charm role

- Charm production as a probe of strangeness in nucleons
- NuTeV, CCFR
  - First measurment of s-quark PDF at Fermilab
    - Deep inelastic neutrino scattering at fixed target experiments



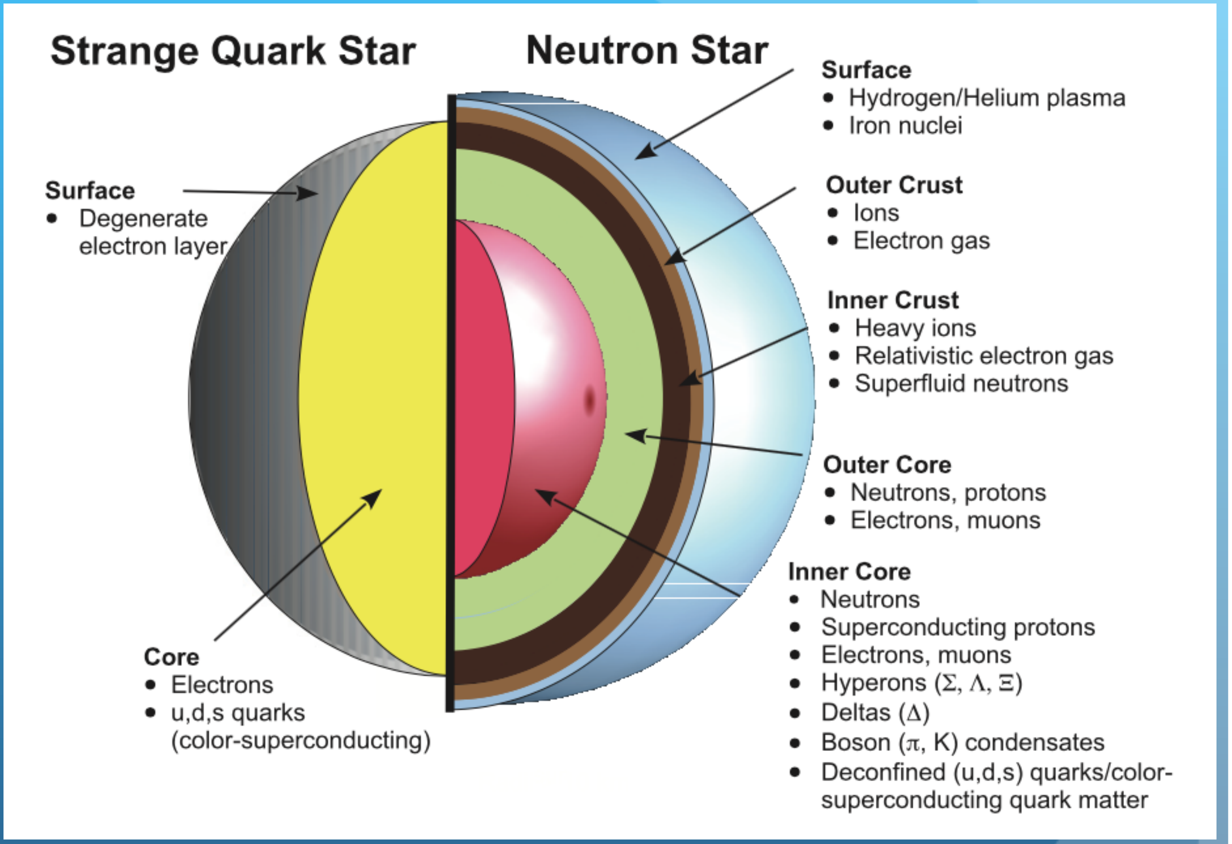
NuTev, PRD 64, 112006 (2001)



CCFR, Phys. Rev. Lett. 70 (1993) 134

Strangeness role

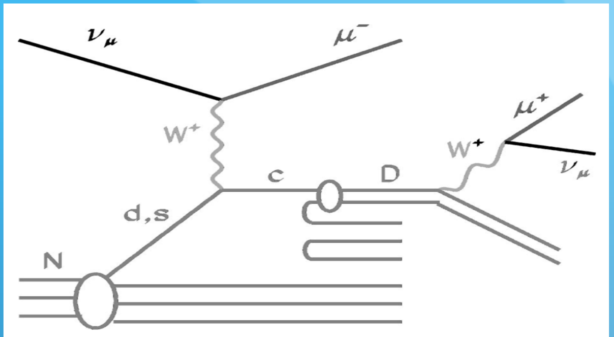
- Heavy ion experiments
  - Normalize their measurement to yields in pp(bar) collisions
    - Strangeness yield in pp(bar) collisions depends on s-quark PDF
  - Strangeness plays a role in various extreme matter models
  - Hypothesized absolutely stable strange u,d,s matter
    - $E/A<E/A_{fe}$
  - With the possibility of forming stable strange matter many neutron stars may be strange

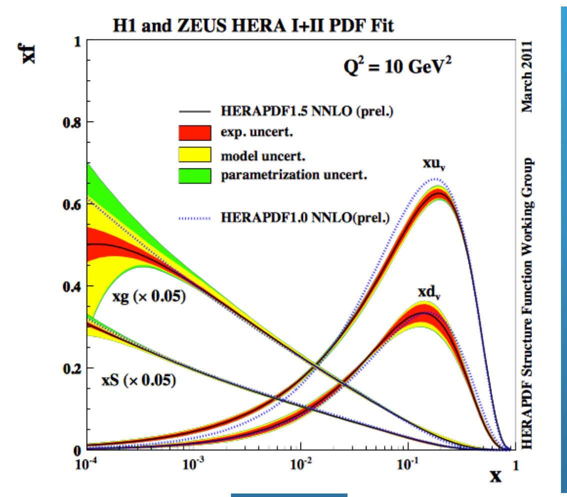


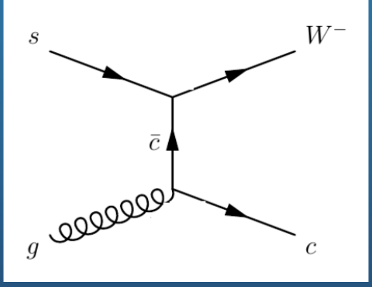
F. Weber et al, Mod. Phys. Lett. A 23 (2014) 1430022

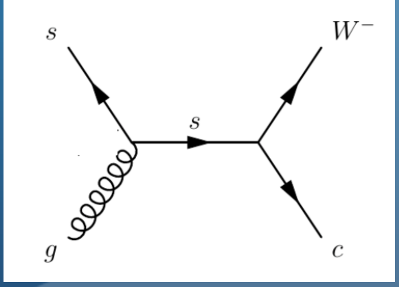
W+c as a probe of s-quark PDF

- NuTeV, CCFR, CHARM II, CDHS measurements of s-quark PDF and content with $30<E_{\nu,\text{anti-}\nu}<600$ GeV at relatively low $Q^2<100$ GeV^2
  - $\kappa=0.39\pm0.07$ $(2S/(U^{bar}+D^{bar}))$
  - $\eta=0.062\pm0.007$ $(2S/(U+D))$
  - $|V_{cd}|=0.225\pm0.008$
  - $|V_{cs}|=0.986\pm0.016$
  - $|V_{cb}|=0.041\pm0.001$ (PDG, 2014)
  - 90% in anti-ν, 50% in ν s-quark initial state
- TeV W+c 85% s-quark initial state, $Q^2<10^4$ GeV^2



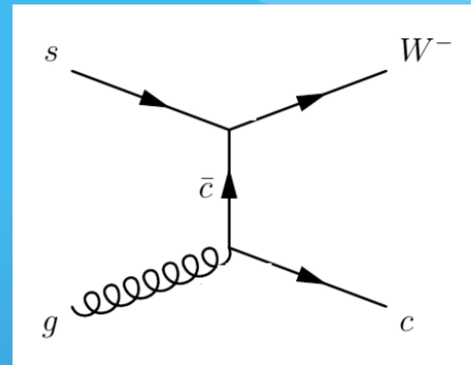


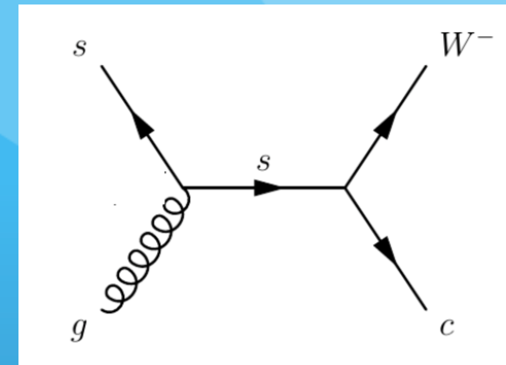


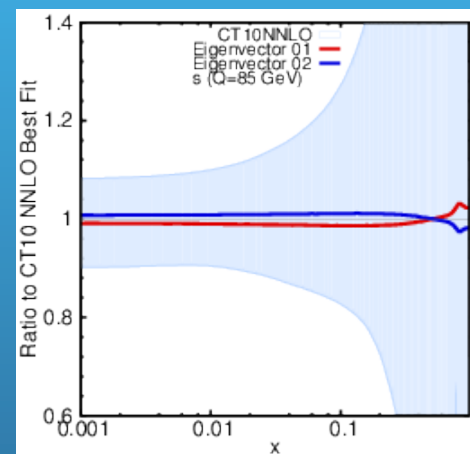


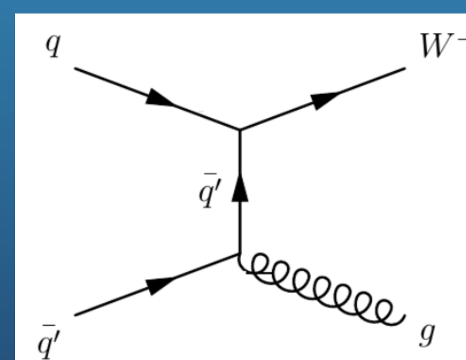
W+c

- gs(d)→Wc
  - 85% s-quark
  - Tuning s-quark PDF
- Current s-quark PDF uncertainties >30% Q^2~7000 GeV^2 (p^{jet}_T~85 GeV)
- s,d-quark gluon fusion channels dominate 20<p^{jet}_T<100 GeV region
  - qq→W+g(g→cc) 25%-45% between 20 <p^{jet}_T< 100 GeV



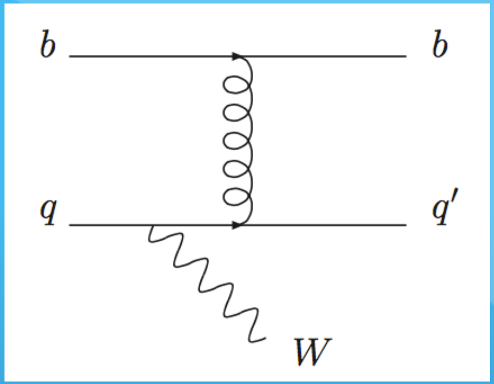


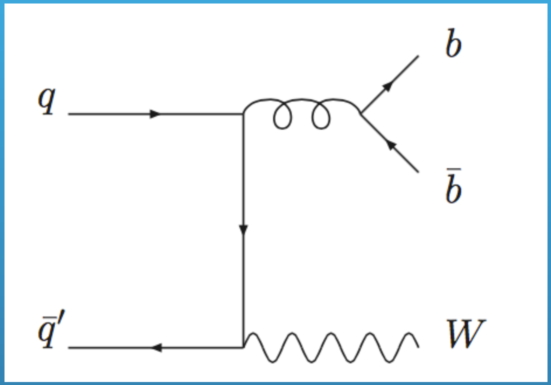


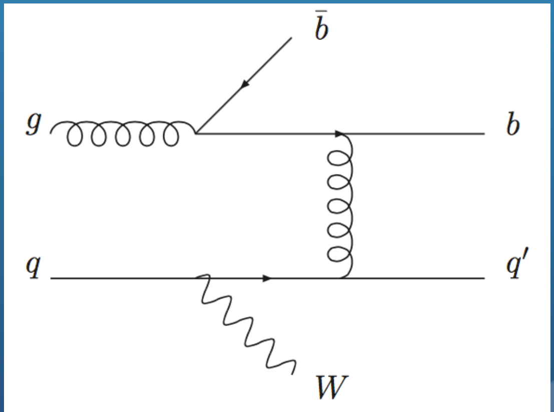


W+b

- Most recent NLO calculations (MCFM)
  - Phys. Rev. D 79 (2009) 034023
- Combinations of older 5 flavor scheme (top plot) in the initial state (m_b=0) with 4 flavor scheme (m_b≠0)
- At Tev (inclusive)
  - qq’→Wbb 11.7 pb
  - bq→Wbq’ 1.62 pb
  - gq→Wbq’ 0.77 pb

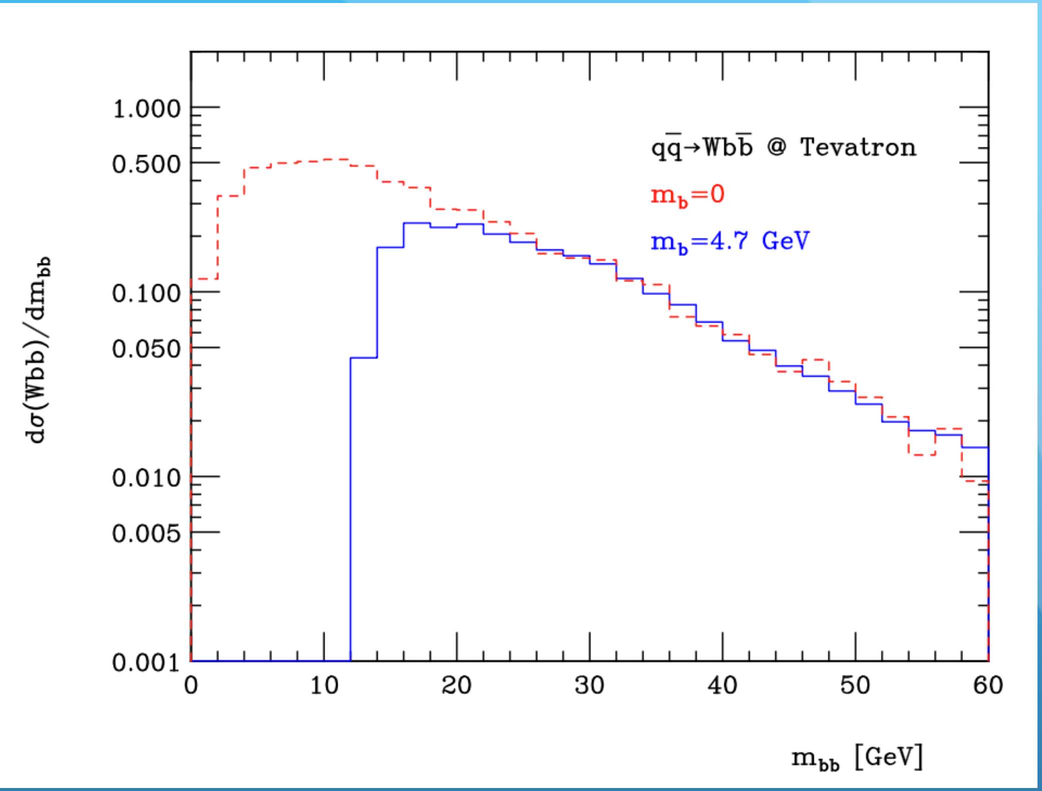


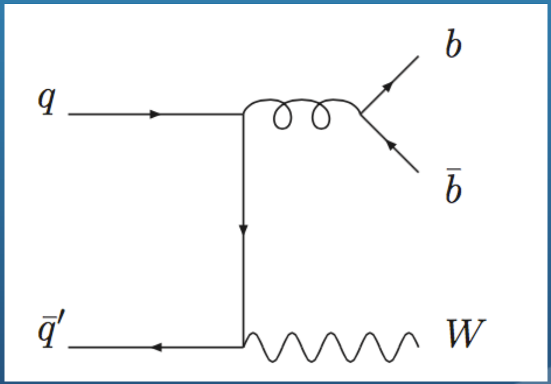




Effect of $m_b \neq 0$

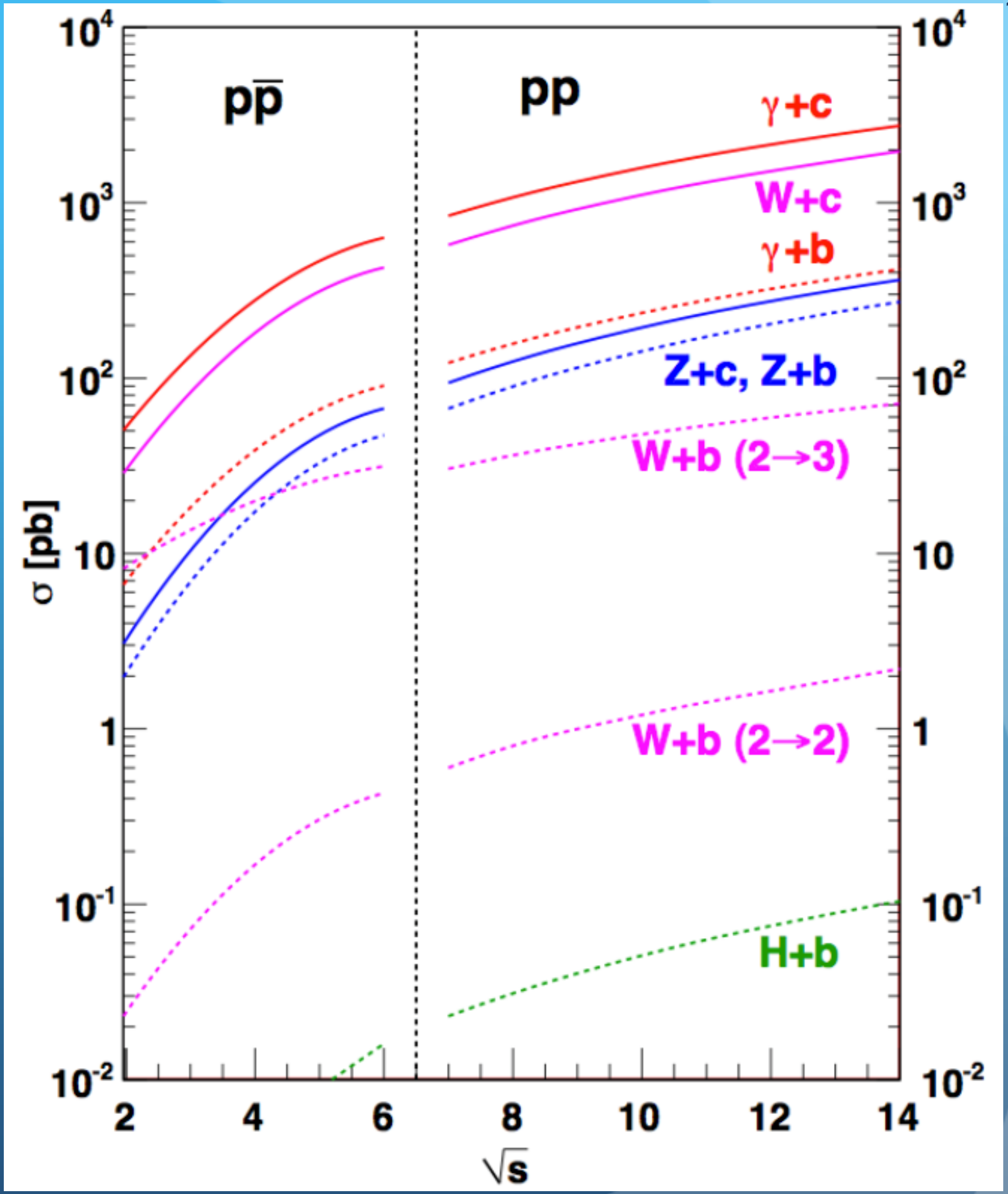
- $m_b=0$ used to overestimate the cross section
- Shown is the cross section W+b inclusive with 1 b not in fiducial





W+c & W+b cross sections

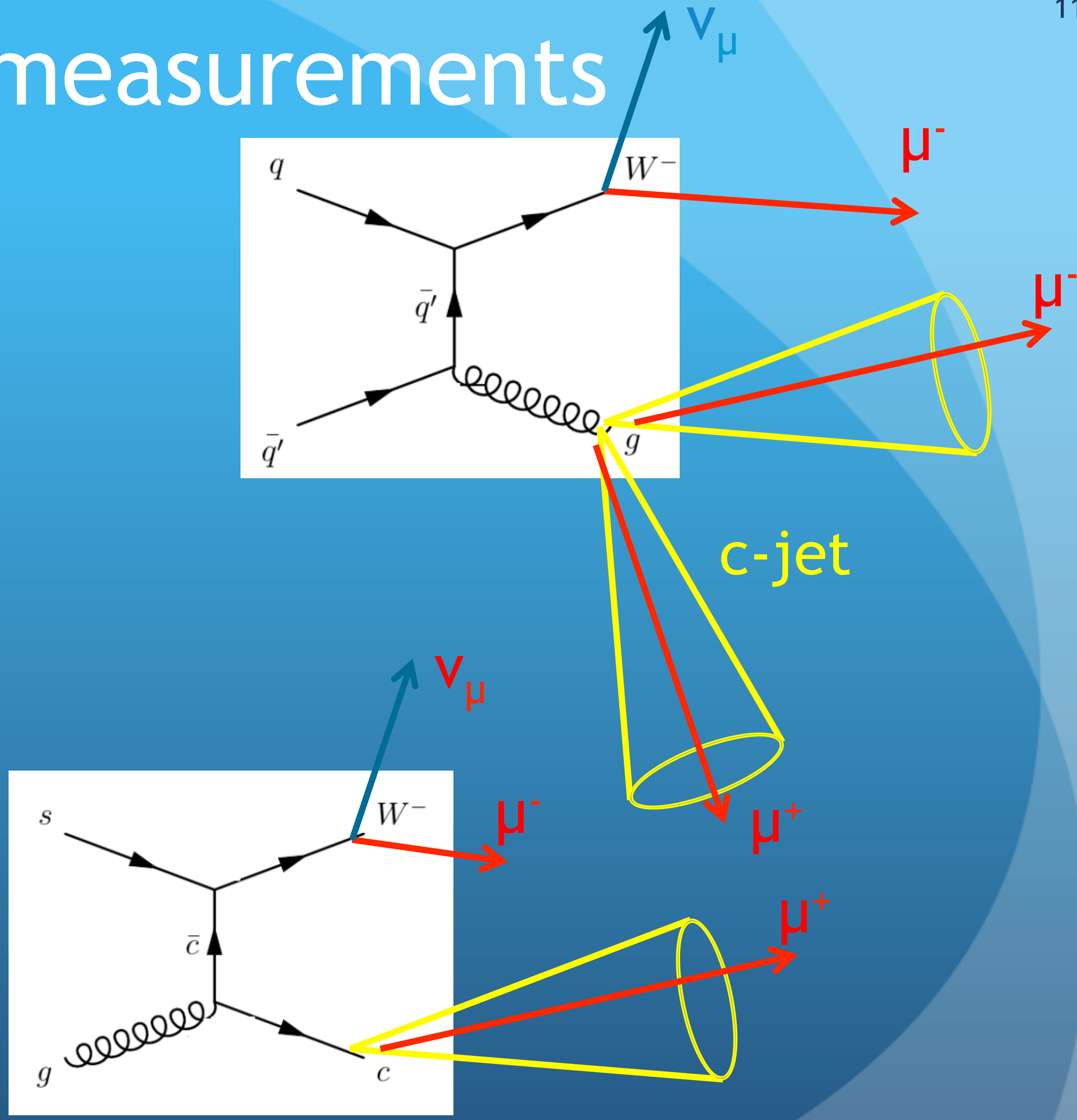
- W boson decay into lepton and neutrino allows clean signal to study QCD through associated production with heavy quark final states (W+c, W+b) otherwise swamped by jet background



J. Campbell

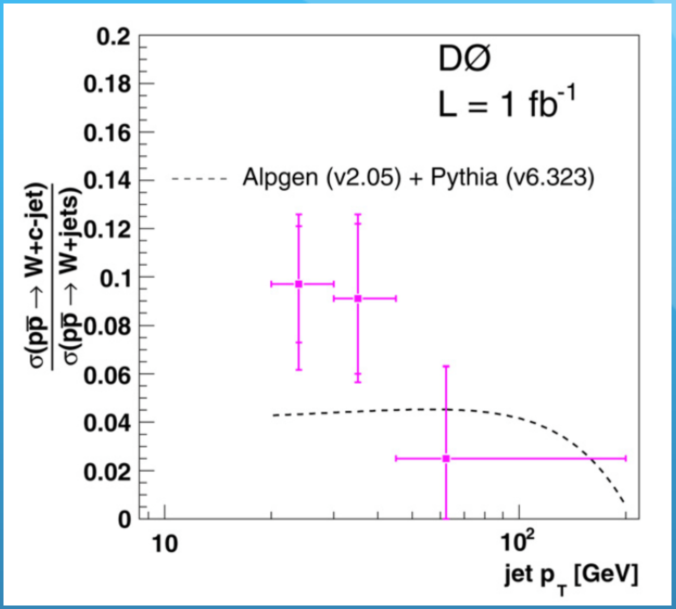
Previous W+c measurements

- Measured at CDF, D0, ATLAS, CMS
- All measurements used soft lepton inside c-jet
  - Signal W+c events have opposite sign (OS)
  - W+cc gluon splitting events have almost symmetric sign
    - Equally OS and same sign (SS)
  - W+cc suppressed by subtracting OS-SS and W+c extracted

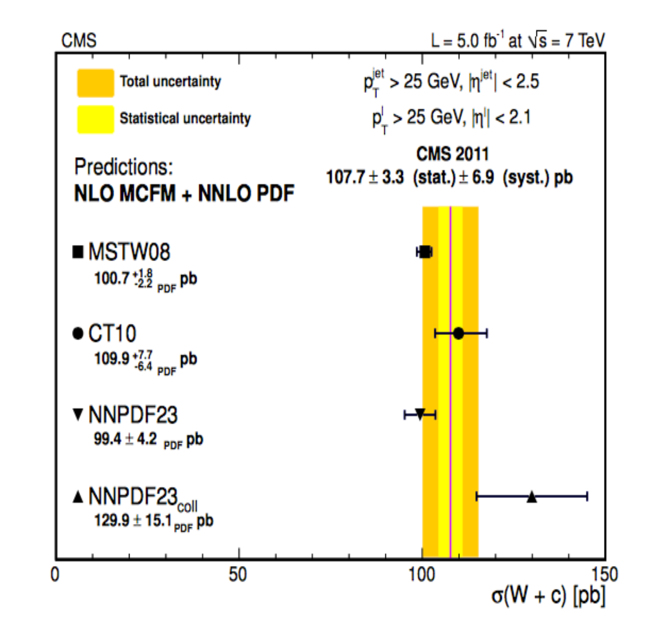


Previous W+c measurements

- D0 measured differentially the ratio of W+c/W+jets cross sections vs p_T^{jet}
  - Cancellation of various systematics



Phys. Lett. B 666 (2008) 23

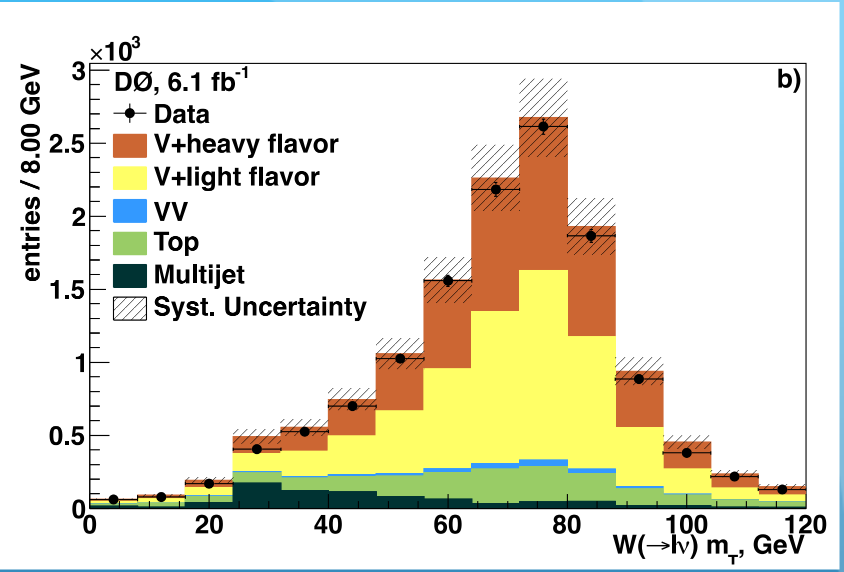


JHEP 02 (2014) 013

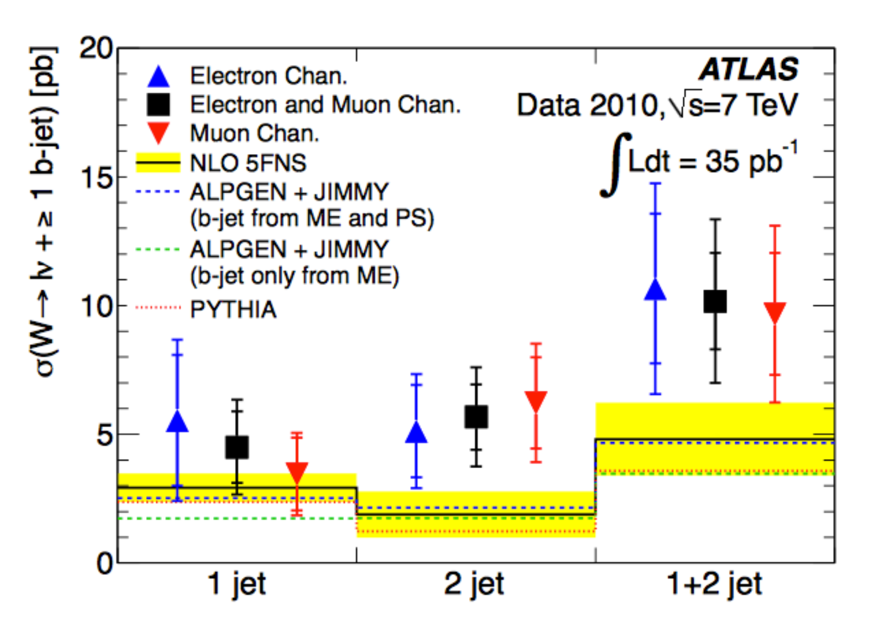
- CDF, ATLAS, CMS measure inclusive cross sections
- Agree with predictions

Previous W+b measurements

- Inclusive total cross sections measured at D0, ATLAS, CDF
  - CDF result uses smaller statistics than D0



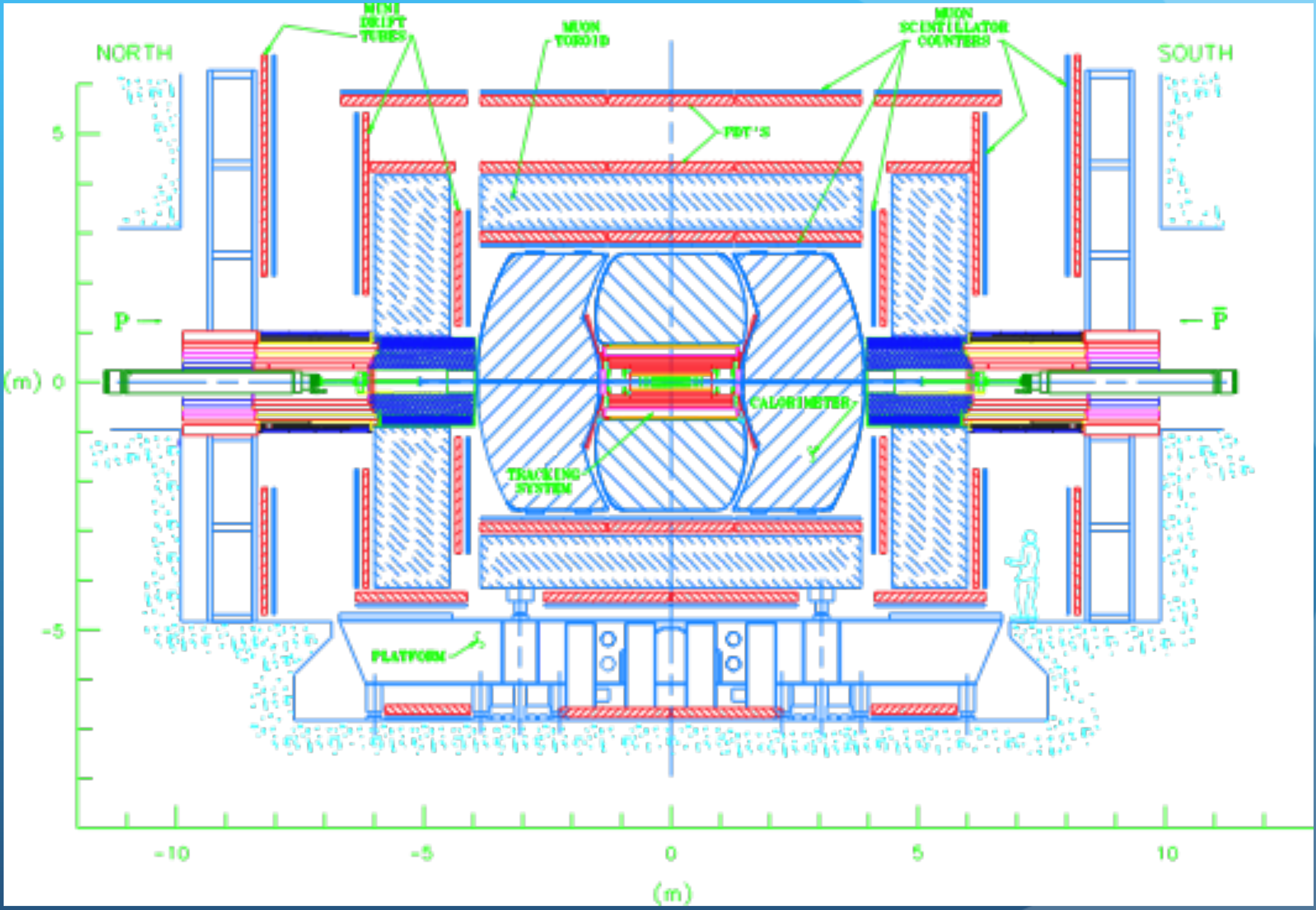
σ·BR=1.04±0.05(stat)±0.12(syst) pb
MCFM: 1.34 pb, MADGRAPH5: 1.52 pb
Phys. Lett. B 718 (2013) 1314



Phys. Lett. B 707 (2012) 418

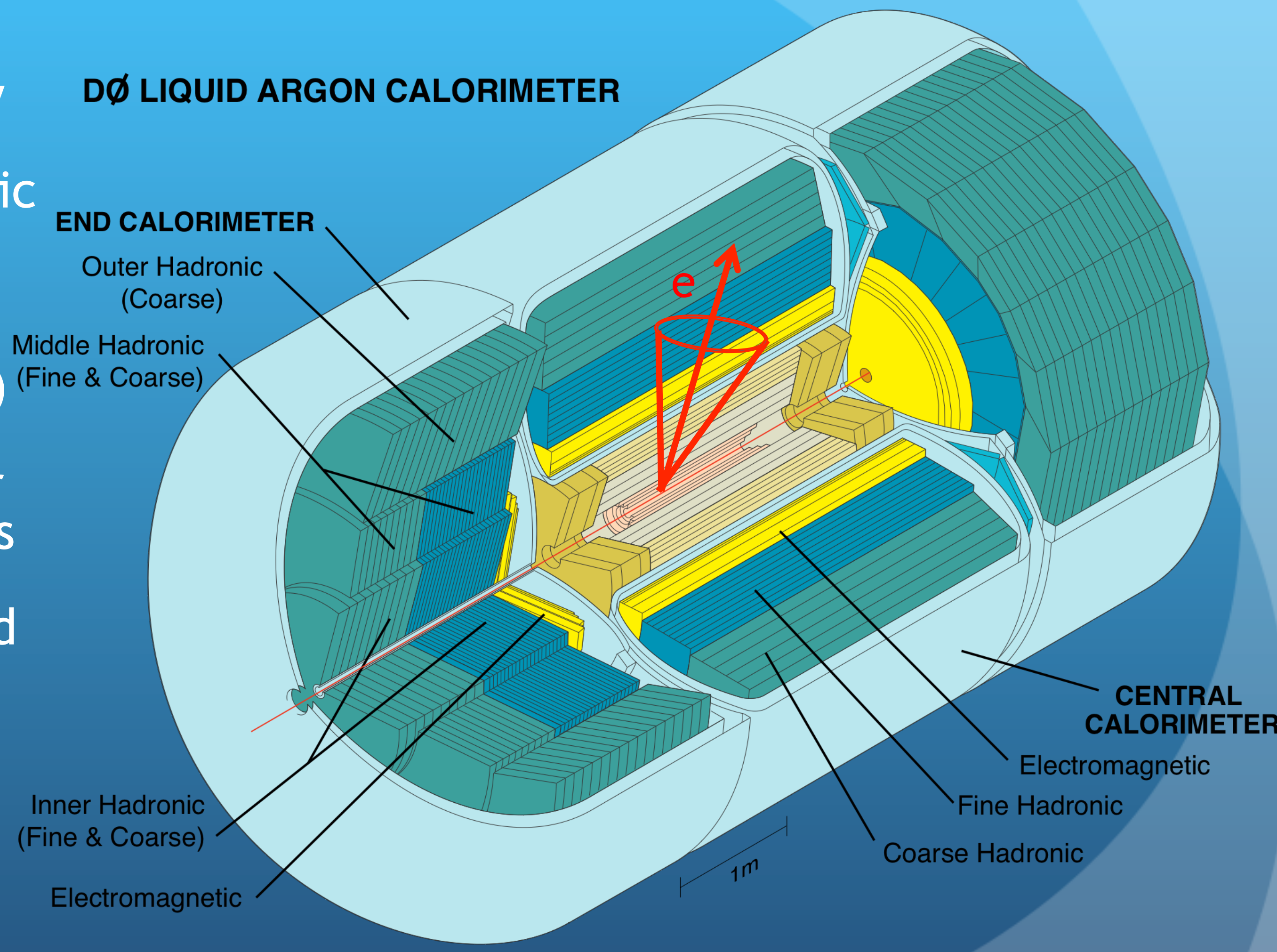
- D0, ATLAS agree with prediction, CDF above predictions

D0 detector


MINI DRIFT TUBES
MUON TOROID
MUON SCINTILLATOR COUNTERS
NORTH
SOUTH
PDT'S
P
P̄
CALORIMETER
TRACKING SYSTEM
PLATFORM
5
(m) 0
-5
-10
-5
0
5
10
(m)

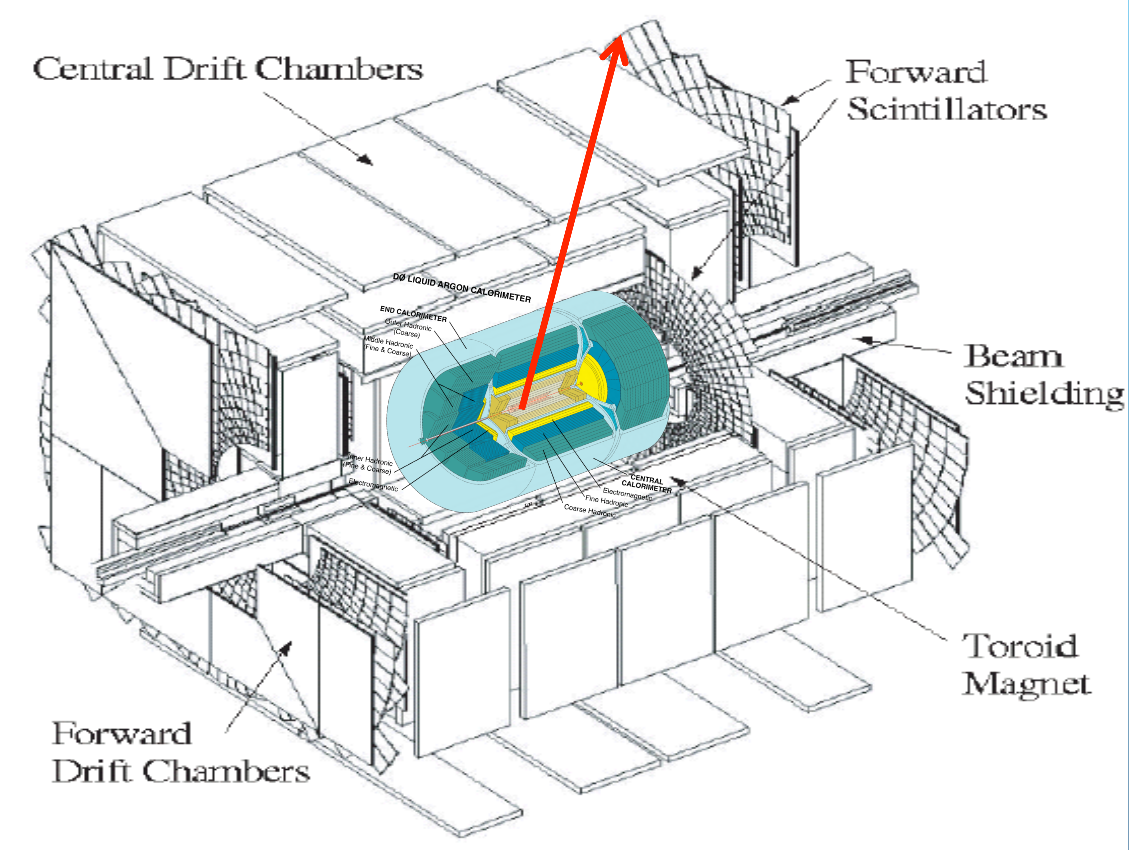
Electron identification at D0

- Cluster with most of energy in the electromagnetic calorimeter
- R=0.2 cone ($R=\sqrt{\Delta\varphi^2+\Delta\eta^2}$)
- Various shower shape variables combined into MVA output and Hmatrix
- Central preshower clusters
- Matched track



Muon identification at D0

- Hits in layer in front of the toroid and 2 layers after
- Matched to a track
- Track isolation (Σ track pt in R<0.5)
- Calorimeter isolation (calorimeter cell energies in R<0.5)

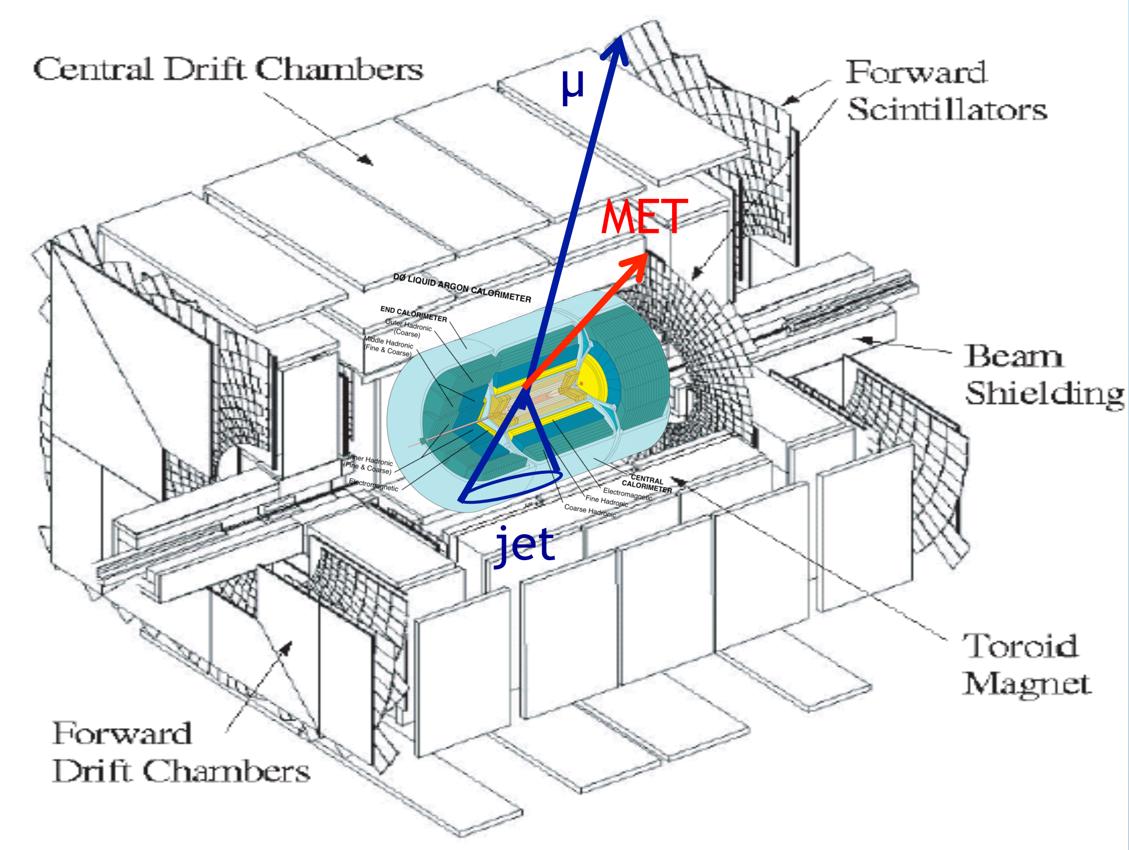


Missing energy identification at D0

- Negative of the vector sum of the transverse momenta of the calorimeter cells excluding coarse hadronic calorimeter (light blue)

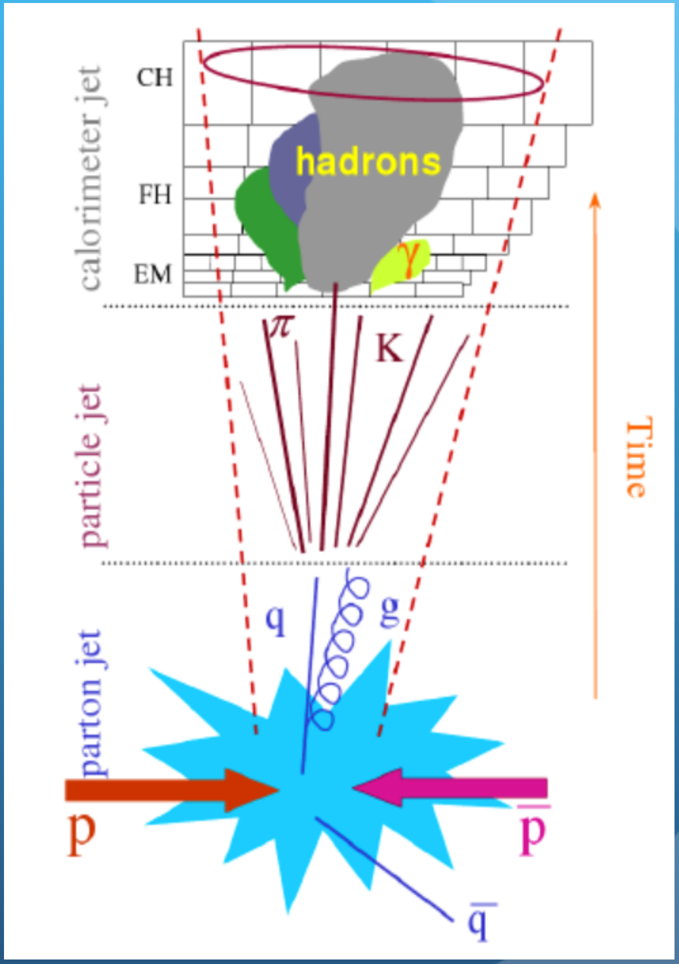
- Correction to calibrate energy from EM objects and jets

- Correction to energy for p_T^μ



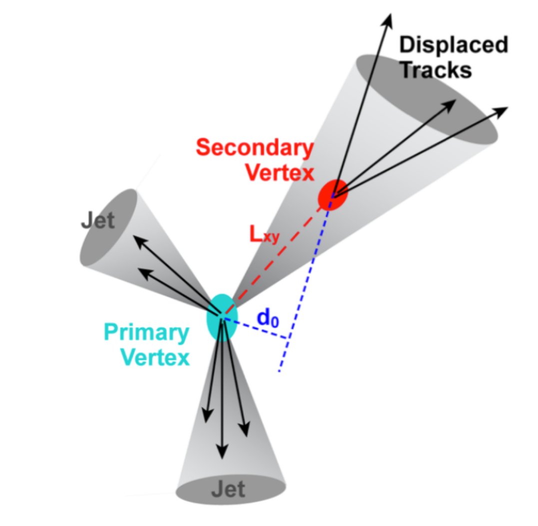
Jet identification at D0

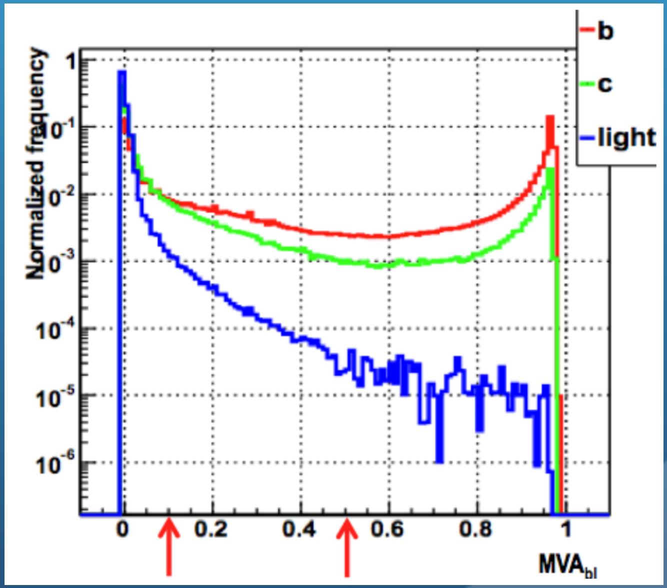
- R<0.5 iterative midpoint cone algorithm
- Jet energy scale (JES) measured in γ+jet or dijet events
- Energy corrected to particle level
  - Detector response, out-of-cone showers, pile-up
- When comparing to theory, the theory has to use parton-to-particle hadronization corrections



Heavy flavor jet ID at D0

- Heavy flavor (b or c) jets decay at ~100-500μm from the primary interaction
- Calculate lifetime probability or identify secondary vertices and compute their mass
- Combine various variables into MVA discriminant
  - Shown efficiency after cut
- Red arrows are cuts on MVA used in the analyses (0.15 actual cut, 0.5 cut for cross checks)
  - Events are selected to be above the cut



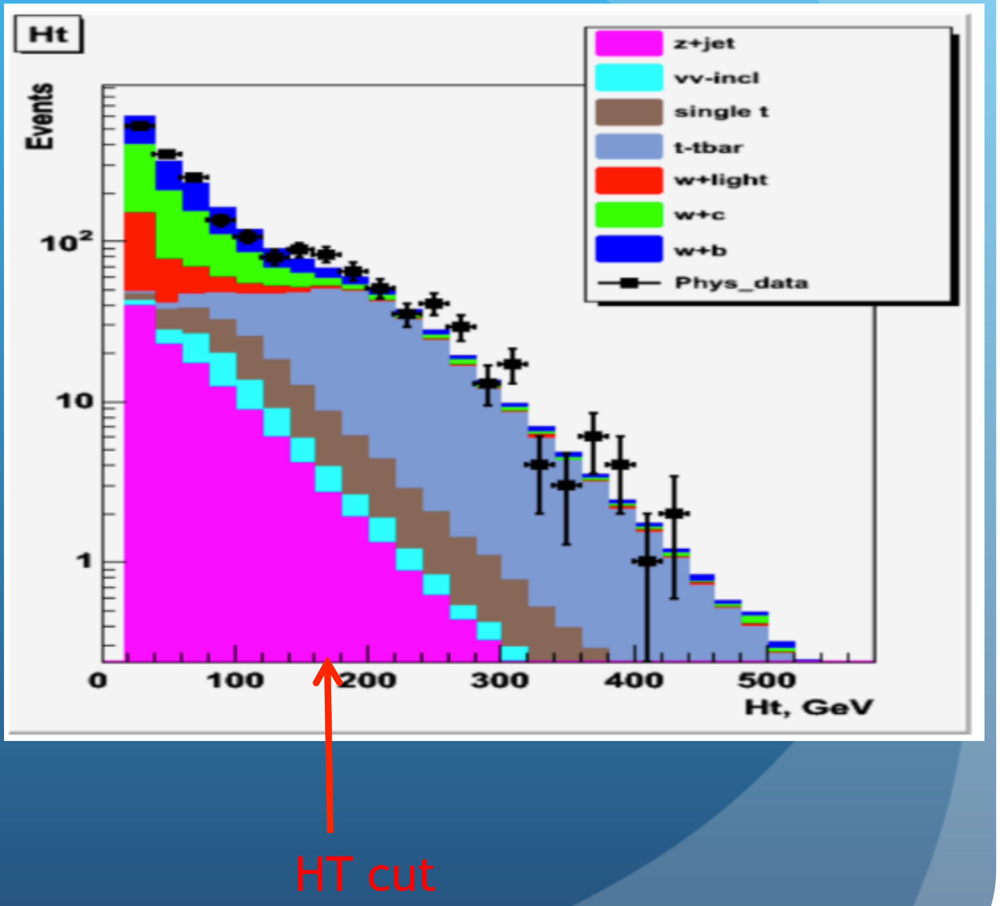


W+b & W+c event selection

- Using $W \rightarrow \mu\nu$ channel and no requirement of soft muon inside a jet
  - Combination of single μ and μ+jets triggers
- $p_T^{\mu}>20$ GeV, $|\eta^{\mu}|<1.7$ (muon reconstruction efficiency ~90%)
- Missing $E_T>25$ GeV, M_T (transverse W mass)>40 GeV
- $p_T^{jet}>20$ GeV, $|\eta^{jet}|<1.5$ (R=0.5 cone jets, p_T^{jet} corrected for JES)
- $H_T= \Sigma_{jets}\, p_T^{jet} < 175$ GeV (against ttbar)
- Required 0.15 cut on HF ID MVA (0.5 for cross check)

W+c backgrounds

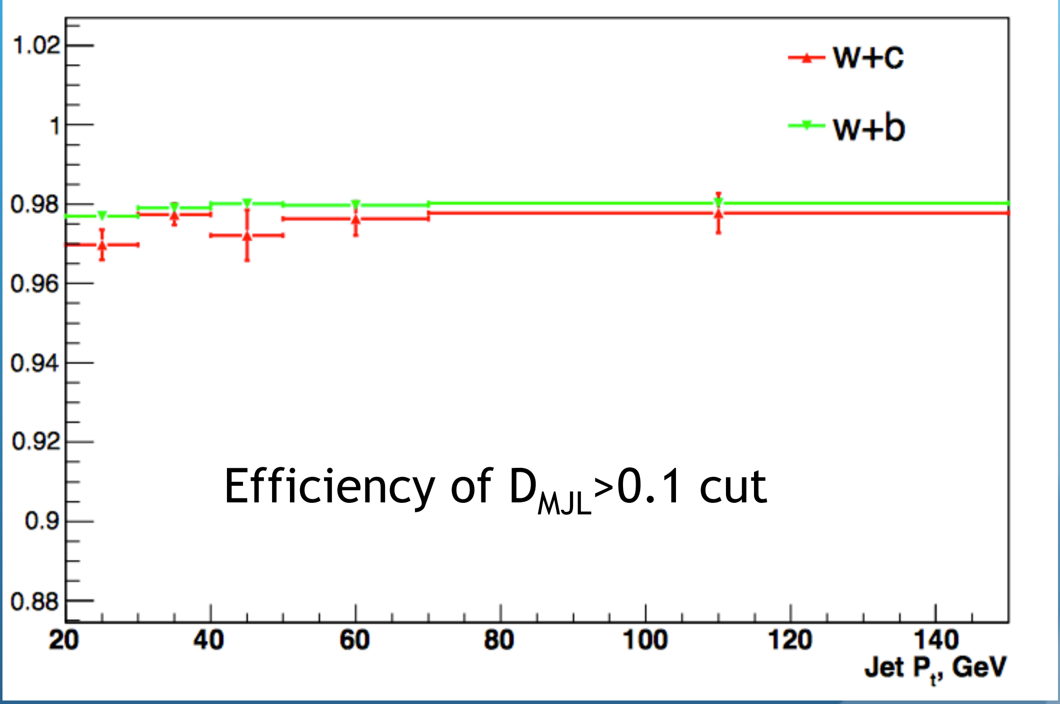
- Data after selection contains jet events, diboson, W+light jets, ttbar
  - Subtract jet events using matrix method (solving a linear system of equations)
    - Efficiencies of different signal and background samples from sidebands are matrix coefficients, data yield (Pass or Fail) is the right-hand side. Solve for signal and background fractions.
- Diboson taken from NLO MC and W+light jets and ttbar at NNLO+NNLL V+jets estimated from LO+PS MC
- Most of the ttbar rejected by the HT<175 GeV cut



D_{MJL} discriminant

- $D_{MJL}=1/2(M_{SV}/5(GeV)-\ln(JLIP)/20)$

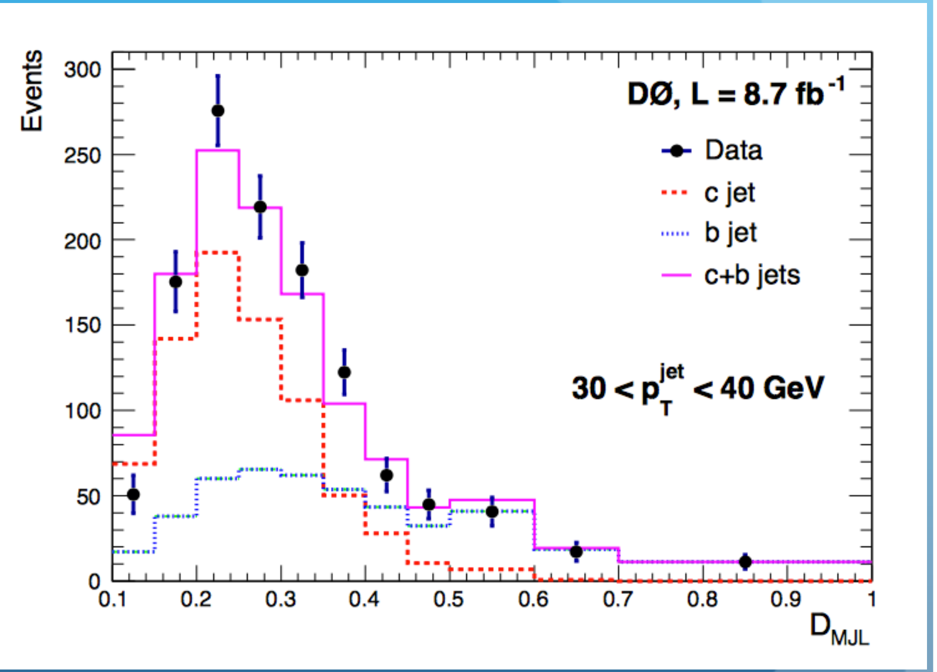
- M_{SV} is the mass of the tracks pointing to the secondary vertex in GeV
- JLIP is the jet lifetime probability (likelihood made of the signed impact parameter significances of the tracks in the jet cone)
- Terms are normalized
- Cut $D_{MJL}>0.1$



Efficiency of $D_{MJL}>0.1$ cut

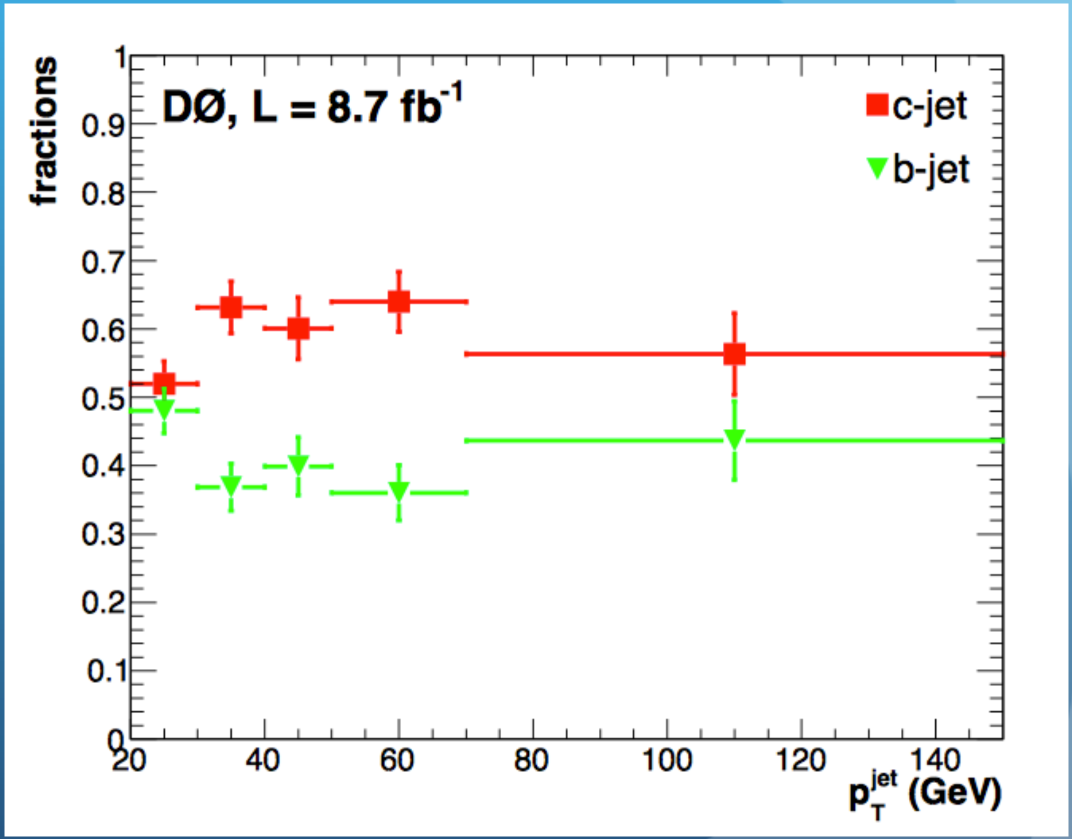
Fit for fractions of W+c & W+b

- 5260 events after background subtraction and D_{MJL} cut
- Build data and W+b, W+c templates of a discriminant
  - $D_{MJL}=1/2(M_{SV}/5-\ln(JLIP)/20)$
- Fit is done in for each p_T^{jet} bin
- Determine fractions from the fit



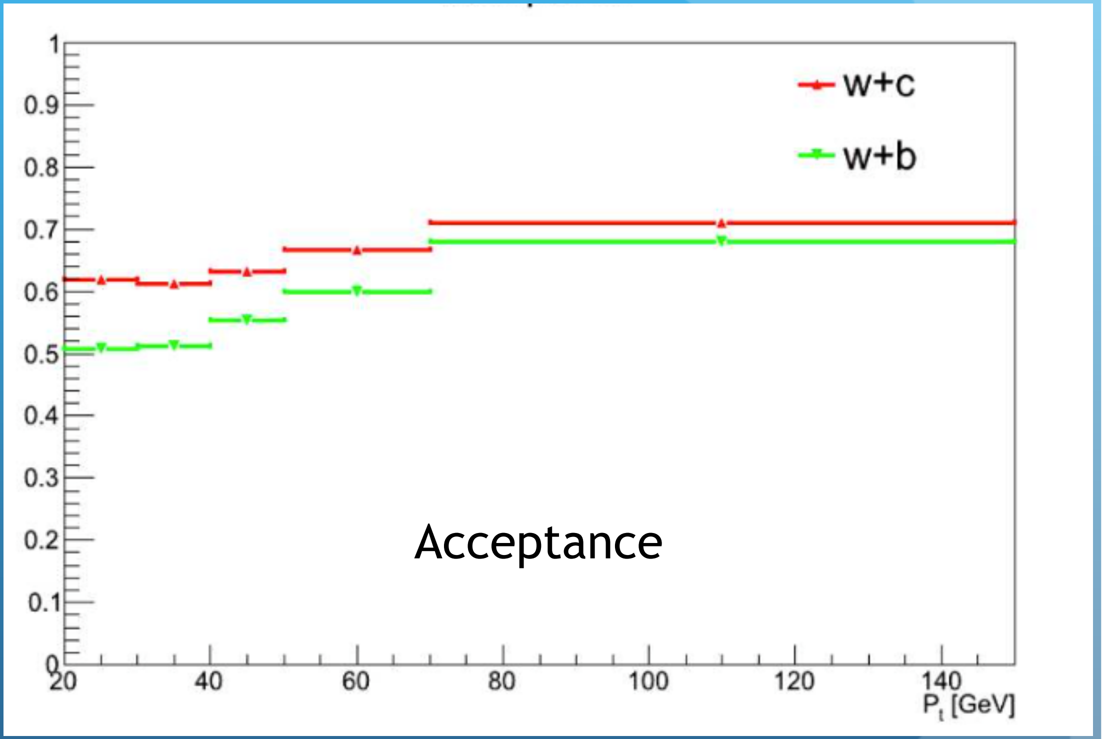
Fitted c and b fractions

- C content slightly higher in medium p_T^{jet} bins
- Weak dependence of b, c, content on p_T^{jet}



Acceptance and efficiency

- Acceptance is calculated in ALPGEN+PYTHIA MC as the ratio of the number of reconstructed events passing basic selection to the number of generated events in the fiducial region
- Efficiency is the efficiency of the ID of muons or jets and the HF ID MVA requirement



W+b & W+c cross section uncertainties

- $\sigma \cdot BR(W \rightarrow \mu\nu) = N_{events}\, f_{b(c)} / (Acc \cdot eff \cdot L)$
- Differential wrt p_T^{jet}
- Systematic uncertainties are shown in %

W+c

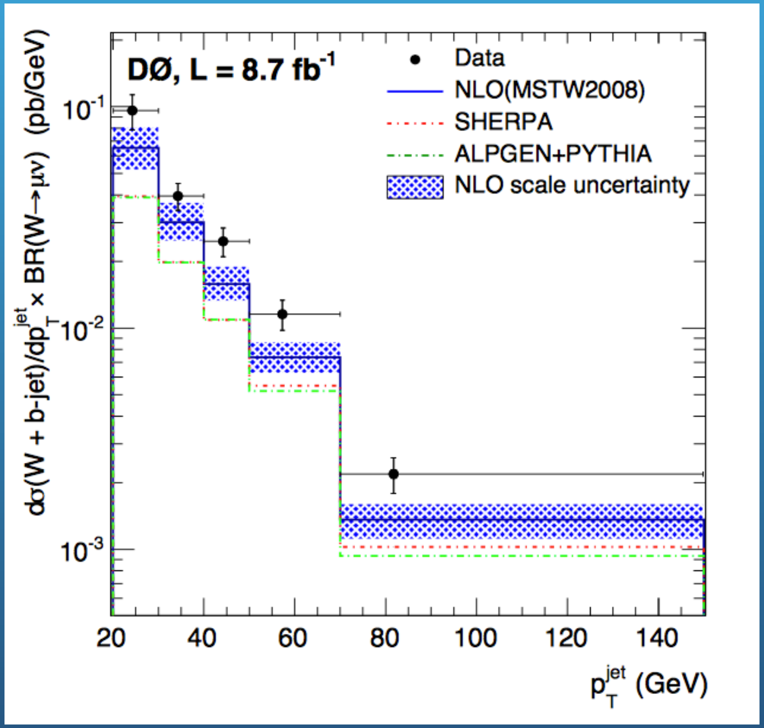
P_T^{jet}, GeV	Muon ID	Lumi	Trigg. eff.	Data JES	Acceptance JES	Acceptance JER	b-ID SF	c-fraction from fit	Bckg. subtr. l-jet	Bckg. subtr. Z+jet, $t\bar{t}$, DB	Tot.
20-30	2.1	6.1	4.4	12.4	4.0	1.4	4.2	6.3	4.0	1.2	17.0
30-40	2.1	6.1	4.4	3.3	1.0	1.3	4.4	6.0	3.2	1.4	11.0
40-50	2.1	6.1	4.4	2.3	1.0	0.3	5.3	7.5	2.6	1.8	11.9
50-70	2.1	6.1	4.4	2.9	1.0	0.1	6.2	6.9	2.3	2.2	12.1
70-150	2.1	6.1	4.4	6.0	1.0	0.4	6.5	10.6	2.2	2.5	15.6

W+b

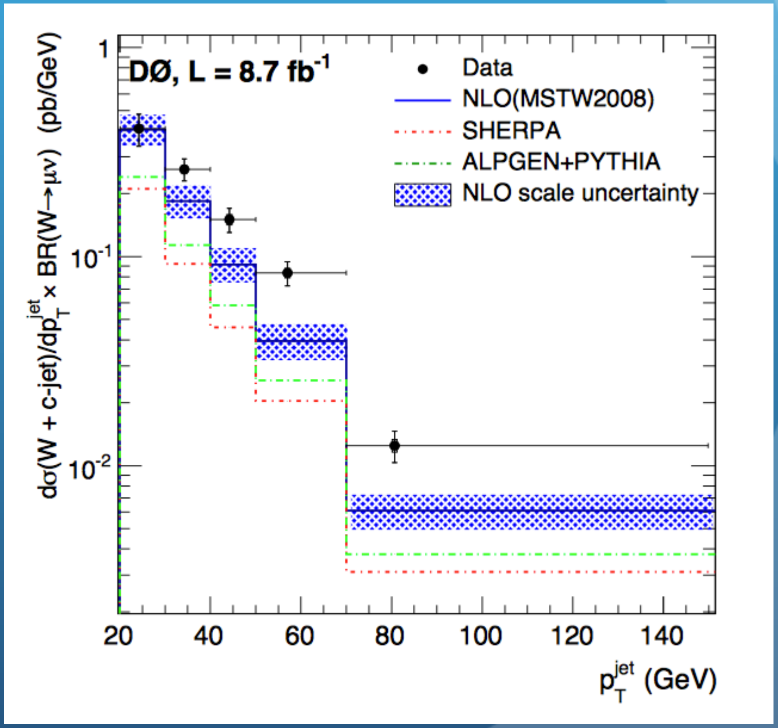
P_T^{jet}, GeV	Muon ID	Lumi	Trigg. eff.	Data JES	Acceptance JES	Acceptance JER	b-ID SF	b-fraction from fit	Bckg. subtr. l-jet	Bckg. subtr. Z+jet, $t\bar{t}$, DB	Tot.
20-30	2.1	6.1	4.4	12.4	4.0	2.3	4.2	6.7	6.0	1.2	17.8
30-40	2.1	6.1	4.4	3.3	1.0	1.1	4.4	9.4	4.8	1.4	13.6
40-50	2.1	6.1	4.4	2.3	1.0	0.4	5.3	10.7	3.9	1.8	14.4
50-70	2.1	6.1	4.4	2.9	1.0	0.3	6.2	11.2	3.4	2.2	15.2
70-150	2.1	6.1	4.4	6.0	1.0	0.5	6.5	13.2	3.3	2.5	17.7

W+b & W+c cross section

- $\sigma \cdot BR(W \rightarrow \mu\nu) = N_{events}\, f_{b(c)} / (Acc \cdot eff \cdot L)$
- Differential wrt p_T^{jet}
- Systematics dominated
  - Total uncertainties lower than in 1 fb^{-1} ratio measurement by a factor of 2-3



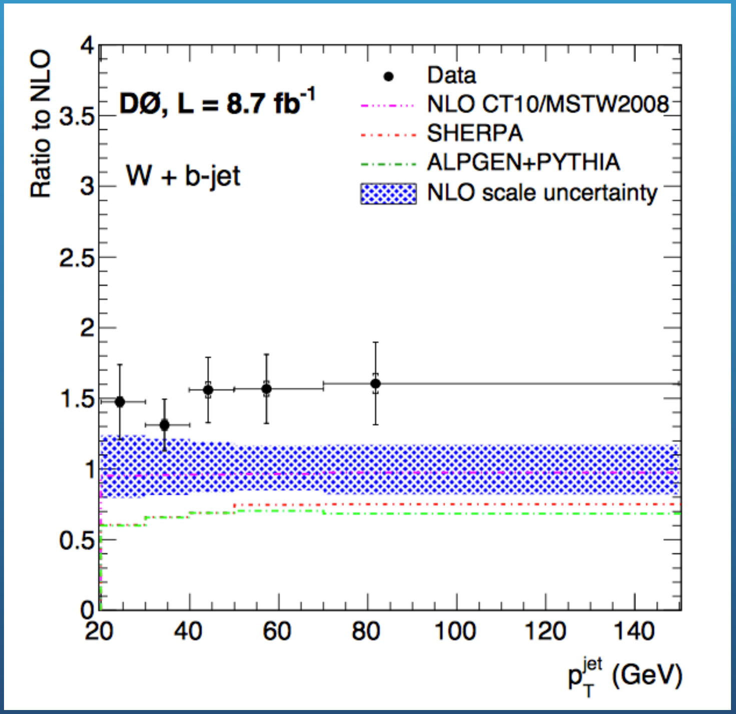
W+b

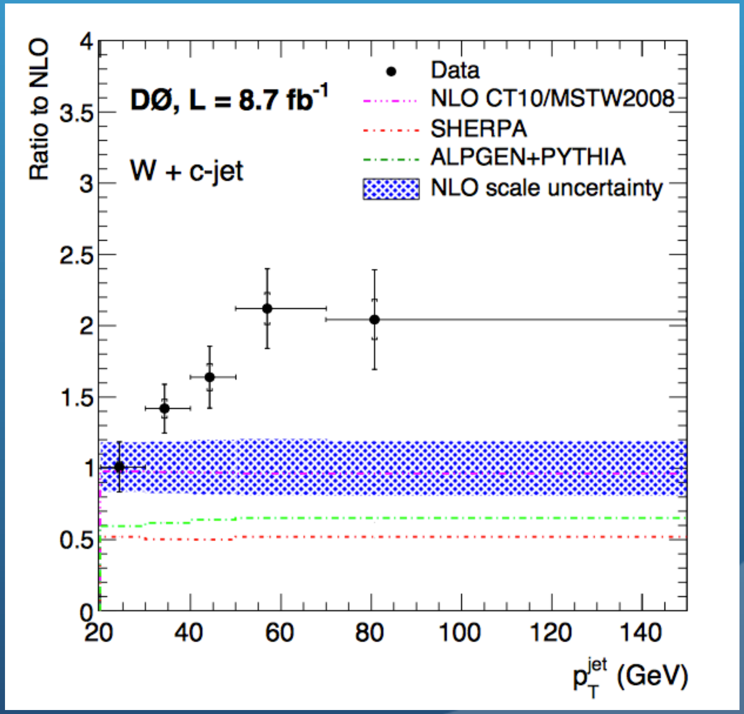


W+c

W+b & W+c ratio to prediction

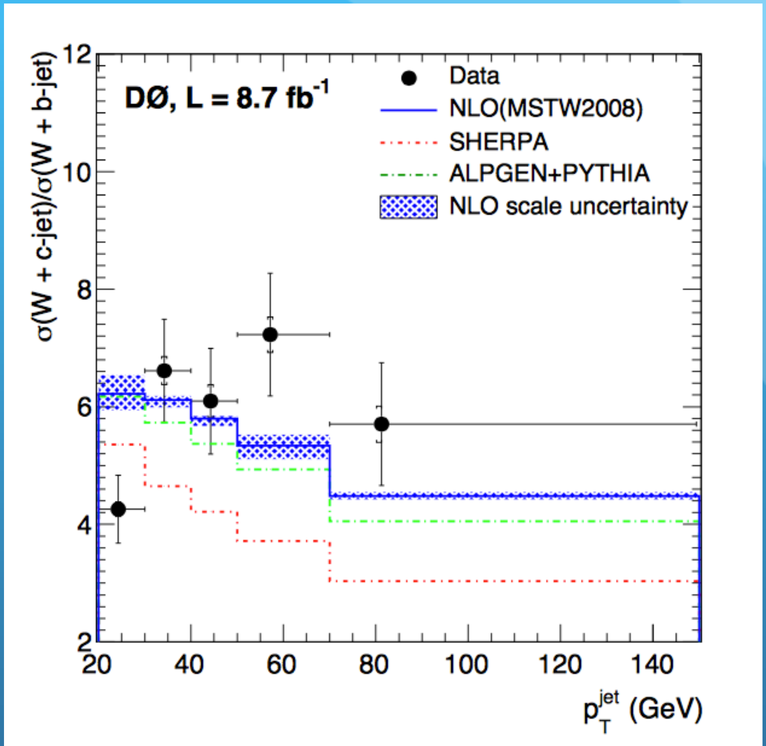
- W+b cross section slightly above NLO (MCFM)
  - Show comparisons with MCFM with CT10 and MSTW08 PDFs
- W+c cross section well above MCFM at p_T^{jet}>50 GeV
  - Region dominated by g→cc
  - For leading order + parton shower (LO+PS) generators agreement with PYTHIA and SHERPA is worse





W+c/W+b ratio & discussion

- W+c/W+b normalization is much better described by MCFM
  - Low p_T^{jet} region is described by SHERPA better
  - Gluon splitting dominated region discrepancy seems to partially cancel out



p_T^{jet} bin (GeV)	$\langle p_T^{jet} \rangle$ (GeV)	Ratio $\sigma(W+c)/\sigma(W+b)$ Data	δ_{stat} (%)	δ_{syst} (%)	δ_{tot} (%)	NLO QCD	SHERPA	ALPGEN
20–30	24.3	4.3	2.9	13.3	13.6	6.2	5.4	6.2
30–40	34.3	6.6	3.6	12.7	13.2	6.1	4.7	5.7
40–50	44.3	6.1	4.6	13.9	14.7	5.8	4.2	5.4
50–70	57.1	7.2	4.2	13.8	14.4	5.3	3.7	4.9
70–150	81.2	5.7	5.4	17.5	18.3	4.5	3.0	4.1

W+c, W+b measurement summary

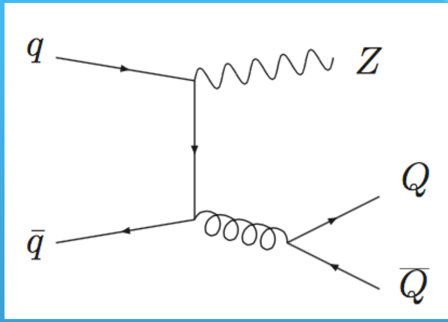
- Performed a differential measurement of W+c, W+b inclusive cross sections vs p_T^{jet}
  - Measurement does not use soft muon inside a jet and allows more sign symmetric $g \to bb$, $g \to cc$ gluon splitting contribution
  - Observe disagreement with MC, small for W+b (especially for $p_T^{jet} > 50$ GeV for W+c, increasingly populated by $g \to cc$)
  - The W+c/W+b agreement better in the gluon splitting populated regions, worse at low p_T^{jet}
- Measurement is systematics dominated
- Uncertainty is lower than the previous D0 differential measurement of W+c/W+jet ratio by of factor 2-3
- Actual increase in precision reached by this measurement may be even higher because various systematics cancel in the previous ratio measurement

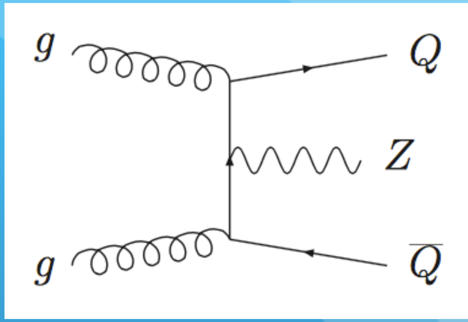
Z+bb/Z+2jets

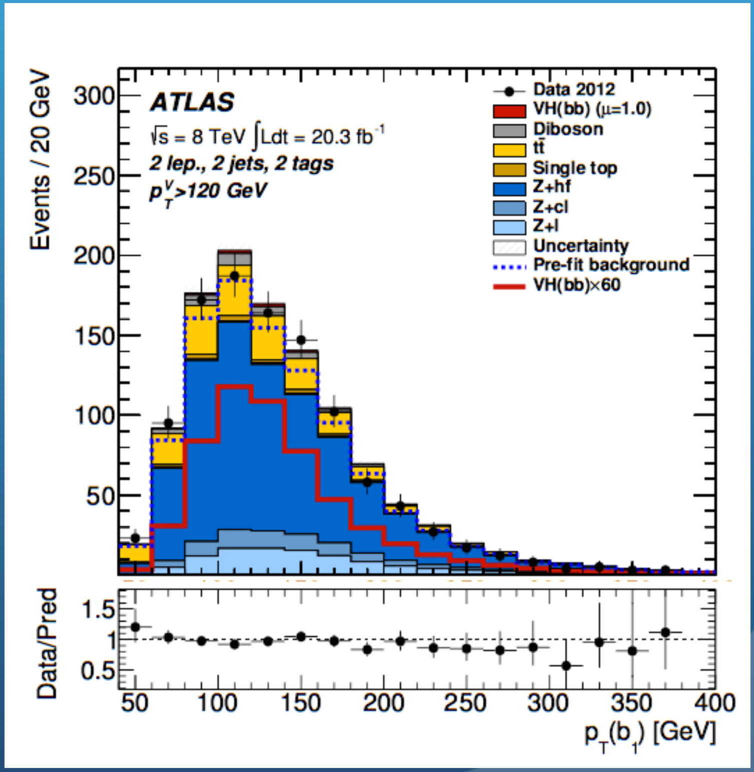
- Measure ratio

  σ(Z+2b)/σ(Z+2jets)

- Z+2b is an important background for ZH(H->bb) and searches for sbottom
- Also important for testing pQCD and non-pQCD (gluon splitting)
- At the Tevatron
  - qq→Zbb 76%
  - gg→Zbb 24%



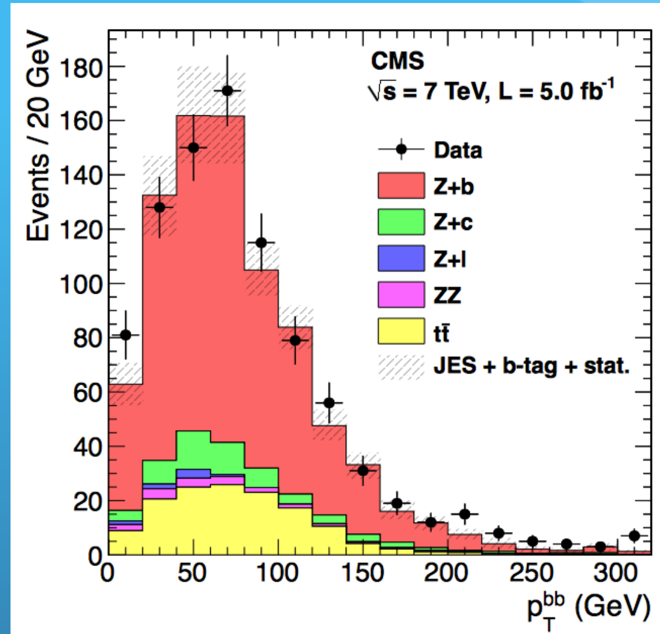




P. Svoisky

Previous Z+2b measurements

- Measured Z+2b cross section and Z+b/Z+j ratio but no Z+2b/Z+2jet
- Can extract Z+2b/Z+1jet
- Overall agreement with simulation



Cross section	Measured
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$

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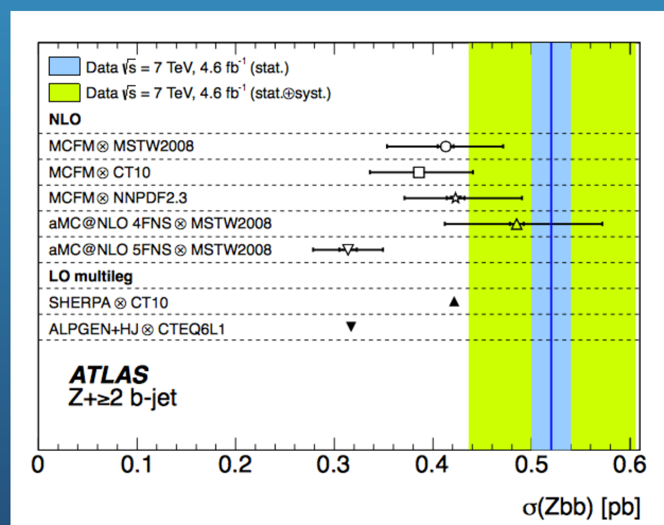

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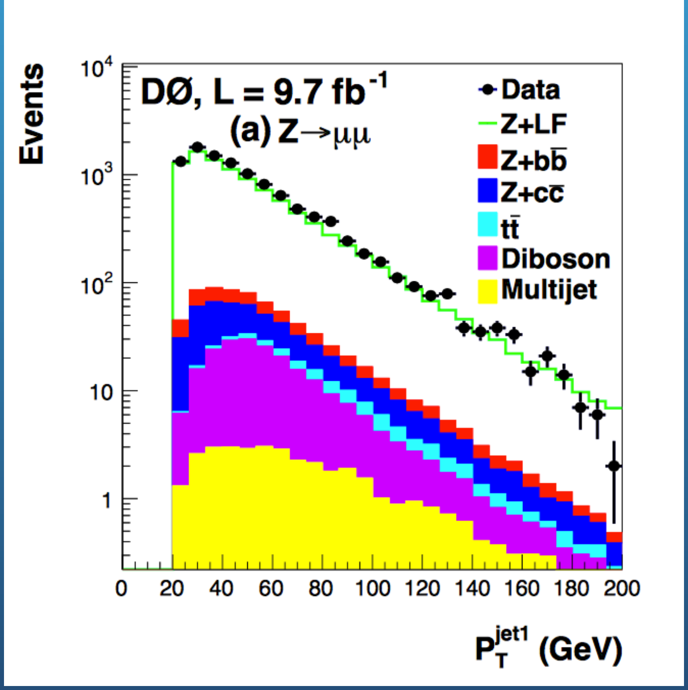
P. Svoisky

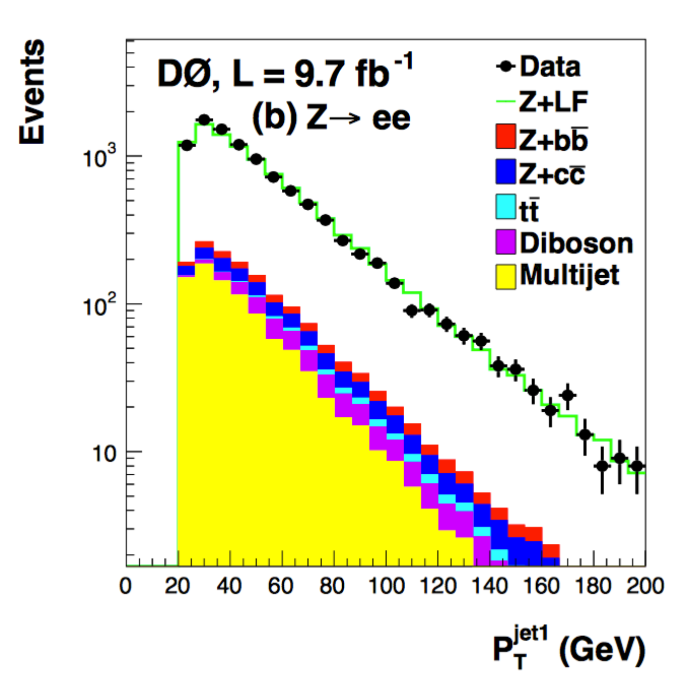
Z+2b/Z+2jets event selection

- Both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels used (and an additional 1 fb^{-1})
- $p_T^l > 15$ GeV, $|\eta^l| < 2$ ($\mu\mu$ additionally required $|\eta_{det}| < 2$)
- $70 < M_{ll} < 110$ GeV
- $p_T^{jet} > 20$ GeV, $|\eta^{jet}| < 2.5$ (p_T^{jet} corrected using JES)
- Miss $E_T < 60$ GeV (against tt)
- At least 2 jets (denominator)
- At least 2 HF ID MVA cut (0.15) passing jets (numerator)

Z+2b/Z+2jet sample composition

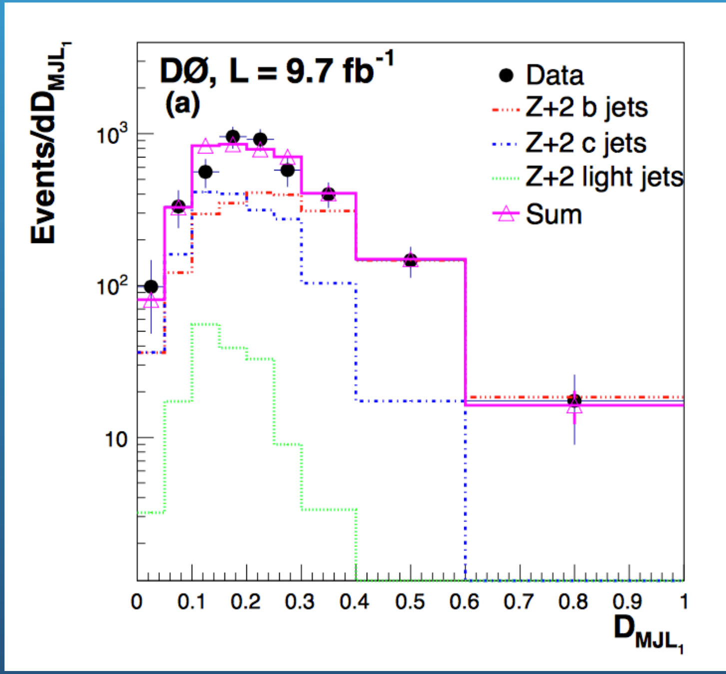
- 20950 events selected (for Z+2jets)
- Jet spectra before HF ID tagging
  - Background dominated by ttbar and diboson
  - ttbar already suppressed by missing E_T<60 GeV cut
- Subtract multijet background using matrix method, ttbar and diboson from simulation

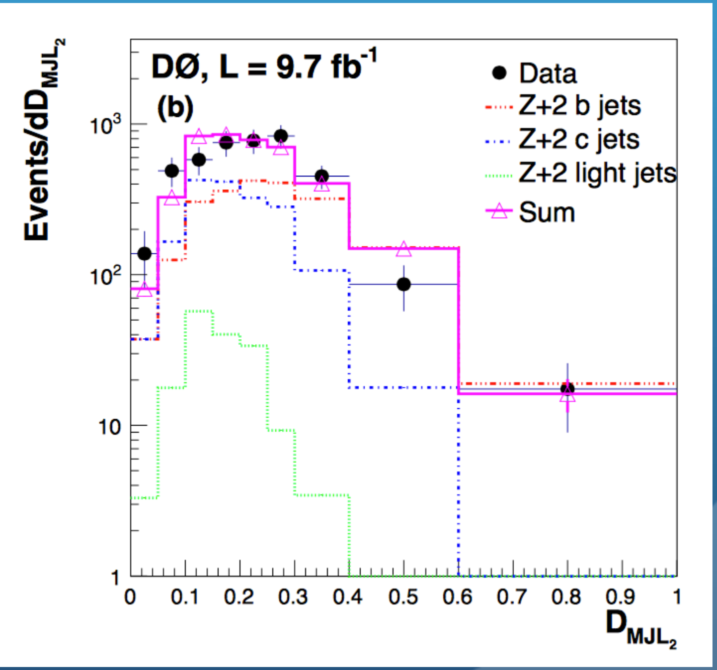




Z+2b/Z+2jets fit for bb fraction

- 241 data events with Z + 2 HF ID tagged jets used for the fit
  - Compute D_{MJL} for each jet
- Fit for Z+2b, Z+2c fractions using D_{MJL} in 2D D_{MJL1}xD_{MJL2} plane (projections on the axes shown)





Z+2b/Z+2jets ratio

$$R = \frac{\sigma(Z+2\ b\ \text{jets})}{\sigma(Z+2\ \text{jets})} = \frac{N_{bb}\, f_{bb}}{N_{\text{incl}}\, \epsilon^{bb}_{tag}} \times \frac{\mathcal{A}_{\text{incl}}}{\mathcal{A}_{bb}}$$

Quantity	Value
N_{bb}	241
N_{incl}	20950
f_{bb}	0.64±0.08(stat)
A_{inc}/A_{bb}	1.09±0.02 (stat)
ε^{bb}_{tag}	0.33

Syst uncert due to	Value (%)
D_{MJL} shape	13.7
H.f. ID efficiency	5.5
b-jet energy calib	2.6
Total	14.9

$\sigma(p\bar{p} \to Z+2\ b\ \text{jet})/\sigma(p\bar{p} \to Z+2\ \text{jet})$

Data $\pm\delta_{\text{stat}} \pm \delta_{\text{syst}}$	δ_{tot}	NLO QCD(MSTW)	PYTHIA	ALPGEN
$(2.36 \pm 0.32 \pm 0.35) \times 10^{-2}$	$0.47{\times}10^{-2}$	$(1.76 \pm 0.26) \times 10^{-2}$	$2.42{\times}10^{-2}$	$2.21{\times}10^{-2}$

Summary

- D0 experiment shows W+c, W+b differential cross section measurements vs p_T^{jet}
  - W+c measurement probes the region dominated by $sg \rightarrow Wc$ at low p_T^{jet}
  - Measurement does not use a soft muon inside a jet and probes the sign symmetric $g \rightarrow bb$, $g \rightarrow cc$ gluon splitting contribution
  - Observed disagreement with data, small for W+b, substantial for W+c for $p_T^{jet} > 50$ GeV, points to the necessity of the addition of higher order corrections to the fixed order predictions as well as insufficiency of the existing gluon splitting model

- D0 measurement of the ratio Z+2b/Z+2jets
  - The ratio of 0.0236 is found with a total uncertainty of 20% using the data statistics of 241 events after HF ID
  - The ratio is measured with precision comparable to the Z+2b cross section measurement by CMS and ATLAS
  - The ratio is in agreement with the predictions by the existing LO+PS (PYTHIA and SHERPA) as well as fixed order NLO MC generators

W+b & W+c cross section

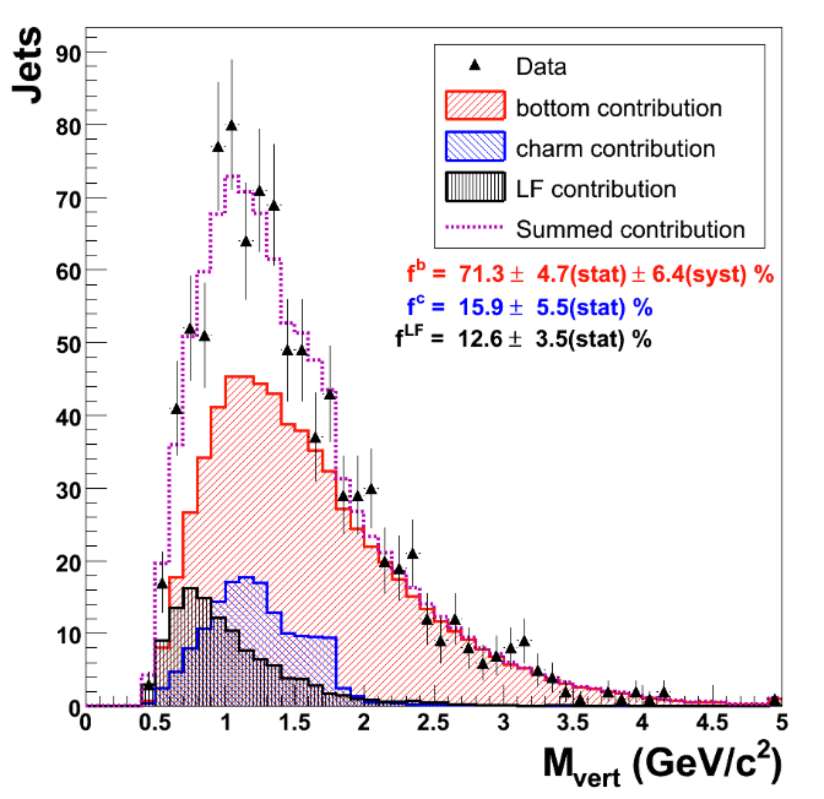
W+c

$p_T^{\rm jet}$ bin (GeV)	$\langle p_T^{\rm jet}\rangle$ (GeV)	$d\sigma/dp_T^{\rm jet}$ (pb/GeV) Data	$\delta_{\rm stat}(\%)$	$\delta_{\rm syst}(\%)$	$\delta_{\rm tot}(\%)$	NLO QCD	SHERPA	ALPGEN
20–30	24.3	9.6×10^{-2}	2.4	17.8	18.0	6.5×10^{-2}	3.9×10^{-2}	3.9×10^{-2}
30–40	34.3	4.0×10^{-2}	2.9	13.6	13.9	3.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}
40–50	44.3	2.5×10^{-2}	3.6	14.4	14.8	1.6×10^{-2}	1.1×10^{-2}	1.1×10^{-2}
50–70	57.2	1.2×10^{-2}	3.4	15.2	15.6	7.4×10^{-3}	5.5×10^{-3}	5.2×10^{-3}
70–150	81.7	2.2×10^{-3}	4.5	17.7	18.3	1.4×10^{-3}	1.0×10^{-3}	9.3×10^{-4}

W+b

$p_T^{\rm jet}$ bin (GeV)	$\langle p_T^{\rm jet}\rangle$ (GeV)	$d\sigma/dp_T^{\rm jet}$ (pb/GeV) Data	$\delta_{\rm stat}(\%)$	$\delta_{\rm syst}(\%)$	$\delta_{\rm tot}(\%)$	NLO QCD	SHERPA	ALPGEN
20–30	24.2	4.1×10^{-1}	3.7	17.0	17.4	4.1×10^{-1}	2.1×10^{-1}	2.4×10^{-1}
30–40	34.2	2.6×10^{-1}	4.6	11.0	11.9	1.8×10^{-1}	9.2×10^{-2}	1.1×10^{-1}
40–50	44.2	1.5×10^{-1}	5.8	11.9	13.2	9.2×10^{-2}	4.6×10^{-2}	5.9×10^{-2}
50–70	57.0	8.4×10^{-2}	5.3	12.1	13.2	3.9×10^{-2}	2.0×10^{-2}	2.6×10^{-2}
70–150	80.7	1.3×10^{-2}	6.9	15.6	17.1	6.1×10^{-3}	3.1×10^{-3}	3.8×10^{-3}

CDF W+b prediction



σ·BR=2.74±0.27(stat)±0.42(syst) pb
PYTHIA:1.10 pb, ALPGEN: 0.76 pb